Normal modes of a radially braced guitar determined by electronic TV holography

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Electronic TV holography has been used to determine normal modes of vibration of a classical guitar having an innovative bracing design. The modes observed at frequencies up to 800 Hz are quite similar to those reported in other classical guitars. Observing modes of the air cavity with stationary plates and ribs helps to understand the normal modes of the guitar. Sound spectra indicate the relative sound radiation by the top and back plates at each modal frequency. © *1999 Acoustical Society of America.* [S0001-4966(99)06011-7]

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INTRODUCTION

Plucking a guitar string causes the instrument to vibrate and radiate sound. The complex vibrations of the guitar body are conveniently described in terms of normal modes of vibration. Each *normal mode* or *eigenmode* can be described in terms of the coupled motion of the component parts, mainly the top plate, back plate, ribs, and air cavity. To understand the acoustical behavior of the instrument, it is desirable to obtain as accurate a description of the normal modes as possible. Unfortunately, it is sometimes difficult to determine the normal modes of vibration of a complex vibrating structure such as a guitar.

When an external force is applied to a guitar body, the amplitude distribution is called an *operating deflection shape* (ODS). This shape is dependent on where and in what direction the force is applied and how the guitar is supported. A normal mode or eigenmode, on the other hand, is an intrinsic property of the guitar. When the guitar is excited at a resonance frequency, the ODS will be determined mainly by one normal mode, but away from a resonance several normal modes will contribute.

In this paper, we describe the use of electronic TV holography to determine the operating deflection shapes, and from these, the normal modes, of a classical guitar having an asymmetric radial bracing design.

I. EXPERIMENTAL METHOD

The TV holography system has already been described (Roberts and Rossing, 1997). The optical system is shown in Fig. 1. A beam splitter BS divides the light from a Nd:YAG laser to produce a reference beam and an object beam. The reference beam illuminates the CCD camera via a phase-stepping mirror PS and an optical fiber, while the object beam is reflected by mirror PM so that it illuminates the object to be studied. Reflected light from the object reaches the CCD camera, where it interferes with the reference beam to produce the holographic image. The speckle-averaging mechanism SAM in the object beam alters the illumination angle in small steps in order to reduce laser speckle noise in the interferograms. Holographic interferograms are displayed on a TV monitor and recorded on a digital printer.

A driving force was applied to the guitar by attaching a small (0.8-g) NdFeB magnet and passing the current from an audio amplifier through a small coil facing the magnet. The guitar was successively driven at the bass end of the bridge (next to the first string), the treble end of the bridge, and at a point just below the center of the bridge. In addition, the guitar was excited acoustically by the sound field from a loudspeaker.

The guitar was supported in a vertical orientation by lightly clamping the neck and letting the tail rest on the air-supported optical table used for holography. Air currents in the room added noise to the holograms of the modes of lowest frequency, but minimal support was preferred in order to minimize distortion of the normal mode shapes. The strings were damped.

''Room-averaged'' sound spectra were recorded on a FFT (fast Fourier transform) analyzer by placing a sound level meter 1 m in front of the center of the guitar while it was driven with band-limited random noise. While room-averaged spectra give only an approximate measure of total radiated sound power, they give a fairly accurate indication of which modes radiate effectively from the front and back of the guitar, and the difference in radiated sound between driving on the treble and the bass sides of the bridge.

In order to understand the normal modes of the guitar, we measured the air-cavity modes with the top and back plates and ribs made stationary by means of carefully fitted sand bags. A hose leading from a horn driver through the sound hole provided a sinusoidally varying pressure to drive the cavity. A microphone was moved around the cavity to locate the nodes and antinodes for the cavity modes.
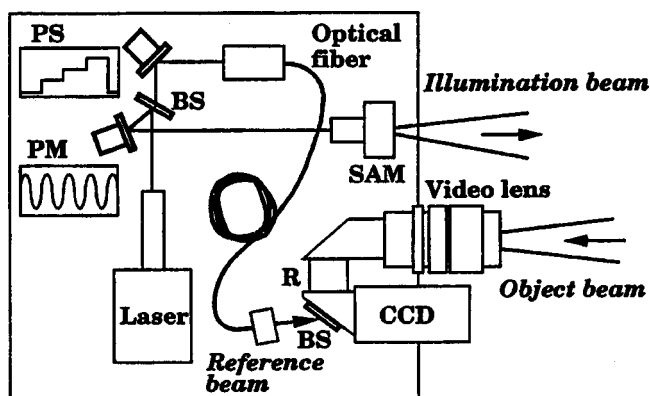
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FIG. 1. Optical system for electronic TV holography.

II. THE GUITAR

The classical guitar used in these studies, constructed by Gila Eban and demonstrated at ISMA98 (Eban, 1998), received favorable comments by those who played it and heard it. The top plate is braced asymmetrically, as shown in Fig. 2. The bars radiate out from the bridge, which is wider on the bass side than the treble side. The back plate combines two transverse bars with radial braces in the lower bout.
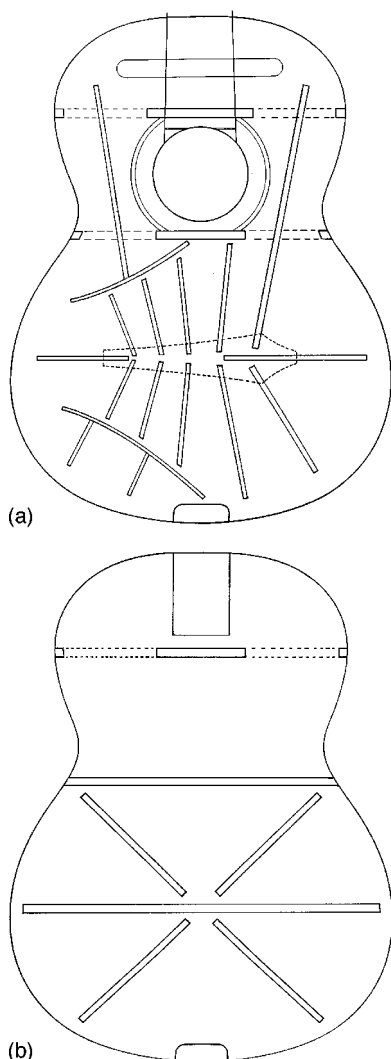

FIG. 2. Bracing patterns in the top and back plates of the guitar.

The spruce top plate varied in thickness from 3.1 mm in the upper bout and and the bass side of the lower bout to 2.9 mm on the treble side. The back, ribs, and bridge were Brazilian rosewood.

III. RESULTS

A. Cavity modes with fixed walls

The lowest cavity mode, the so-called Helmholtz or sound-hole resonance, was found at 124 Hz. This compares closely to the sound-hole resonance frequencies found in two classical guitars and also to those found in three folk guitars of the ''dreadnaught'' design (Rossing *et al.*, 1985). It may seem a little surprising that the sound-hole resonance frequencies would be the same in the larger folk guitars, but the sound holes in these larger bodies were proportionately larger as well. Unfortunately, some investigators have confused the true Helmholtz or sound-hole resonance, which requires stationary plates, with the first normal mode of the guitar, which occurs about 25% lower in frequency.
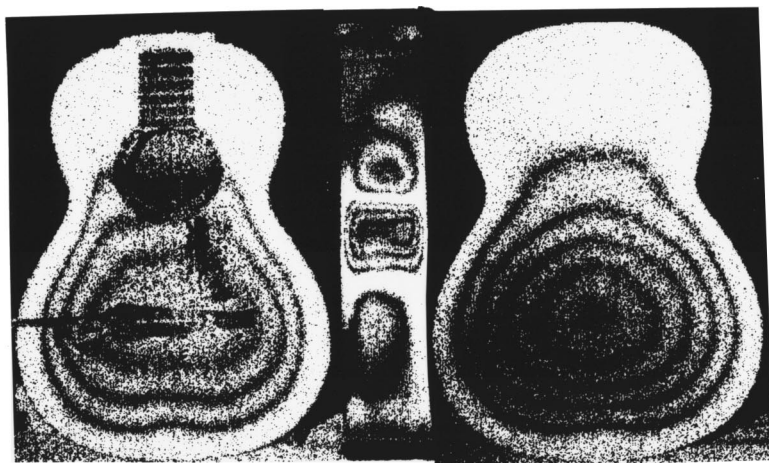
The next cavity mode, the longitudinal (0,1) mode, which has pressure maxima at the two ends of the guitar as well as in a plane halfway between them, occurs at 417 Hz. The transverse (1,0) mode, having pressure maximum at the ribs as well as halfway between them, occurs at 571 Hz. These are comparable to those found in other classical guitars, but are somewhat higher than those in the larger dreadnaught-style folk guitars (Rossing *et al.*, 1985). They are lower than those calculated by Roberts (1986) for a guitar-shaped cavity with a zero-pressure boundary condition at the soundhole, however.

The longitudinal (0,2) cavity mode was found at 785 Hz, and the transverse (2,0) mode was found at 1043 Hz, again at higher frequencies than measured in folk guitars and close to those calculated by Roberts (1986) using finite element methods. Finally, the (1,1) mode, having both a longitudinal and a transverse plane at which the sound pressure is maximum, was found at 792 Hz.
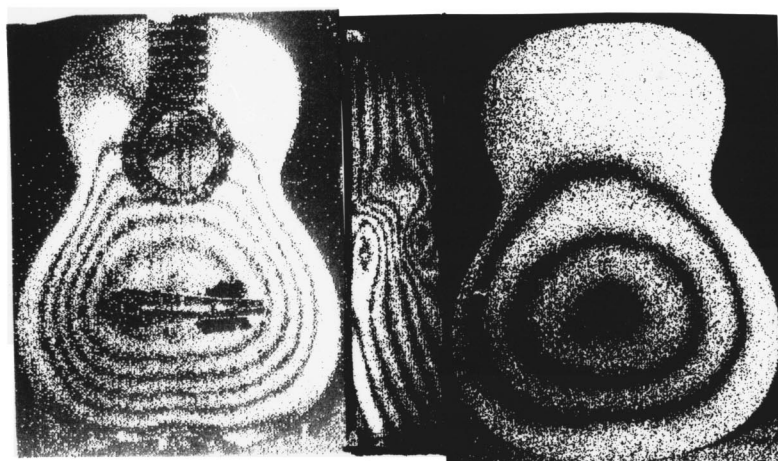
B. Normal modes of vibration

In most guitars, the frequency response in the range of 100 to 220 Hz is dominated by three normal modes which result from strong coupling between the (0,0) Helmholtz or sound-hole resonance with the so-called (0,0) modes in the top and back plates (Fletcher and Rossing, 1998). This guitar is no exception. In the first mode at 101 Hz, shown in Fig. 3(a), the lower parts of the top and back plate move in opposite directions so that the guitar ''breathes'' through the sound hole. It should be mentioned that the force amplitudes used to make the interferograms of the top, back, and ribs were not the same.
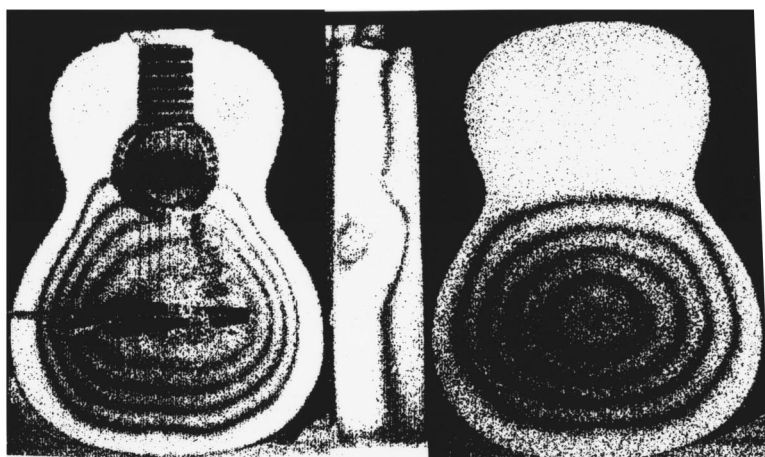
In the second mode at 155 Hz, shown in Fig. 3(b), the top and back plates move in the same direction and the ribs move in the opposite direction. When the guitar rests on its side so that one of the ribs is constrained, this mode becomes slightly asymmetrical and its frequency increases to 184 Hz. In the third mode at 210 Hz, the top and back plates again move in opposite directions, but the air flow in the sound hole is opposite in phase to that observed in the mode an

(a)

(b)

FIG. 3. Three normal modes that result from strong coupling between the (0,0) modes in the air cavity, the top plate, and the back plate: (a) 101 Hz; (b) 155 Hz; and (c) 210 Hz. Force amplitudes are not the same in the various interferograms.

(c)

octave lower at 101 Hz. These three modes, which result from coupled motion of top plate, back plate, and cavity modes having similar shapes, have been shown to be consistent with a ''three-mass'' model (Christensen, 1982).

In the next mode at 304 Hz, shown in Fig. 4, a longitudinal nodal line appears in both the top and back plates. Air ''sloshes'' from side to side inside the cavity, although the frequency of this mode is well below the (1,0) cavity resonance. This mode was observed at 303 Hz in a Kohno 30 classical guitar (Rossing *et al.*, 1985), at 275, 295, and 296 Hz in three Ramirez guitars (Caldersmith, 1989), and at 268

Hz in a classical guitar by Richardson (Richardson and Roberts, 1985), who points out its importance to the tonal characteristics of classical guitars. This mode generally occurs at somewhat higher frequencies in folk guitars having a stiffer top plate (e.g., at 377 Hz in a Martin D-28; see Rossing *et al.*, 1985).

The mode at 407 Hz, shown in Fig. 5, features longitudinal bending of the top and back plates, although the nodal patterns are different in the two plates. The nodes in the back plate appear to be located at the transverse braces, while the node in the top plate appears just above the bridge. Meyer
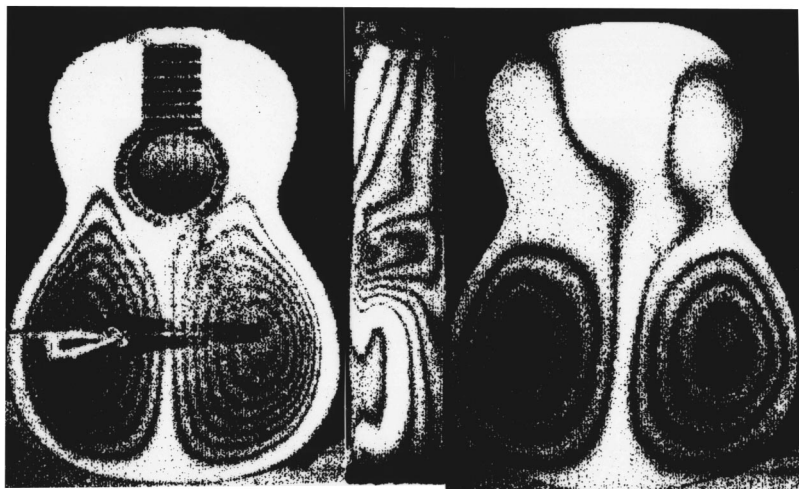
FIG. 4. Mode at 304 Hz characterized by ''see-saw'' motion of the top and back plates while air ''sloshes'' back and forth internally.

(1983) found the strength of the radiation from this mode to be the most important single factor in determining guitar quality. In a Kohno 30 classical guitar, a similar longitudinal mode was found at 427 Hz, although the back had a single transverse node, while in three Ramirez guitars it was observed at frequencies of 420, 424, and 428 Hz (Caldersmith, 1989). In a Martin D28 folk guitar, a similar mode was observed at 404 Hz (Rossing *et al.*, 1985). The longitudinal cavity mode occurs at 383 Hz in the Martin D28 compared to 417 Hz in the guitar described in this paper.

Two longitudinal nodes appear in the mode at 613 Hz, shown in Fig. 6. Modes with similar patterns of vibration in the top plate have been observed in classical guitars at 553 Hz (Richardson and Roberts, 1985) and 590 Hz (Rossing *et al.*, 1985), although the back plate patterns are different. Caldersmith (1989) observed this mode at 585, 586, and 600 Hz in three guitars by Ramirez and at 420 to 662 Hz in other classical guitars. It is generally weak or missing altogether in folk guitars.

Above 700 Hz, the effective coupling between the top and back plates is quite weak and modes appear independently in the top and back plates. Figure 7 shows a back plate mode at 774 Hz, excited by the sound field of a loudspeaker, in which the vibrational pattern correlates well with the bracing pattern used in the back plate. A rather similar modal pattern was observed at 760 Hz in a radially braced top plate by Marty *et al.* (1987).

C. Radiated sound

Room-averaged sound pressure levels 1 m from the top plate and from the back plate are shown in Fig. 8. The lowest mode at 102 Hz radiates primarily from the sound hole, so it shows up more strongly in front of the top plate. The modes at 155 and 210 Hz appear to be radiated equally well by the top and back plates, however.

The ''see-saw'' mode at 304 also radiates strongly from both the top and back plates even though the microphone is close to the center plane where the radiation should be weak if the mode were exactly symmetrical. Apparently a small asymmetry leads to a monopole component in the sound radiation field. The longitudinal mode at 407 Hz leads to stronger radiation from the back plate than from the top plate, it appears. This is a little surprising in light of the important role Meyer (1983) apparently found for this mode in determining the quality of classical guitars.

The mode at 613 Hz, having two longitudinal nodes in both the top and back plates, appears to radiate slightly more sound from the top plate, as does the (1,1)-type mode (not
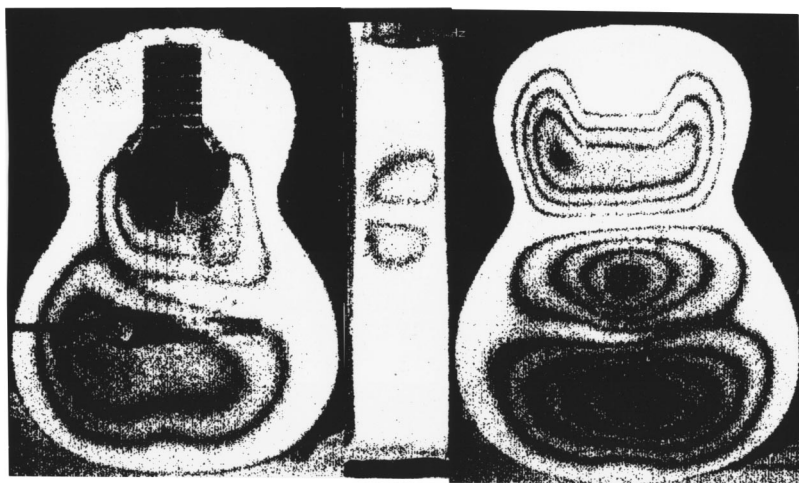

FIG. 5. Mode at 407 Hz features longitudinal bending of the top and back plates.
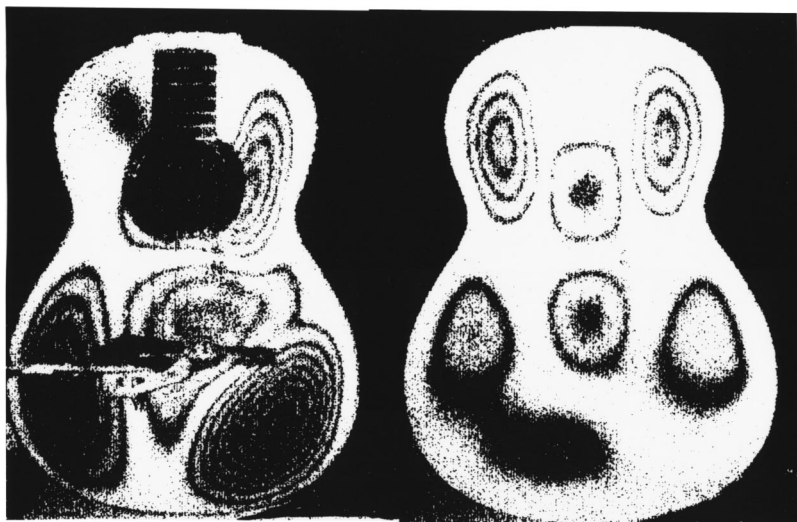
FIG. 6. Transverse bending mode at 613 Hz with two nodes.

shown) at 588 Hz. The mode at 810 Hz, however, radiates more strongly from the back.

IV. DISCUSSION

Compared to violins, which have reached a state of maturity, guitars are still evolving. Exciting experiments are taking place in acoustics laboratories, as well as luthiers' workshops, around the world. These experiments have ranged from the use of new materials and new systems for bracing the body to developing whole new families of instruments (Caldersmith, 1989).

The bracing pattern in the classical guitar described in this paper is substantially, though not radically, different from that used in traditional classical guitars. Some of the design philosophy is discussed in a recent paper given at ISMA98 (Eban, 1998). Radial bracing in the top plate appears to offer some advantages over the more traditional fan bracing. It allows the luthier to vary the effective mass of the low-order modes in the top plate, a desirable goal (Richard-

son, 1998), and yet keep the normal mode frequencies at the desired locations. This is one of the first guitars in which radial bracing has been used in the back plate as well, and it apparently encourages the back plate to vibrate in modes such as the one shown in Fig. 7. Further studies are needed to document the acoustical advantages or disadvantages.

An earlier model was constructed with a divided bridge, which is believed to have resulted in the absence of a (2,0) mode such as the one found in this guitar at 613 Hz (Eban,
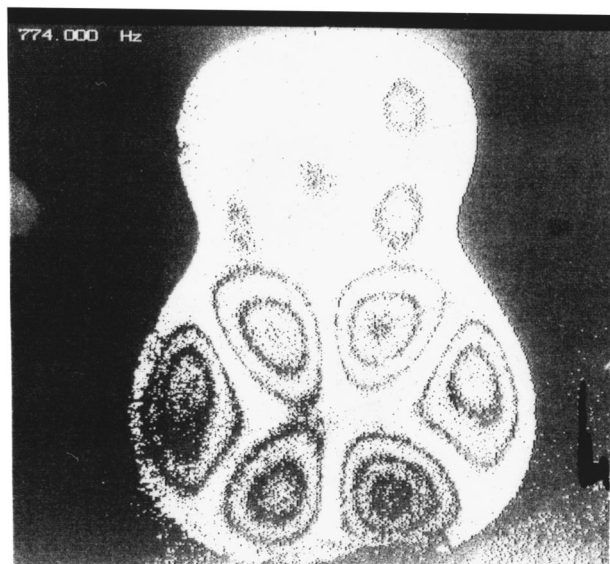

FIG. 7. Back plate mode at 774 Hz in which the vibrational pattern correlates well with the bracing pattern in the back plate [Fig. 2(b)].
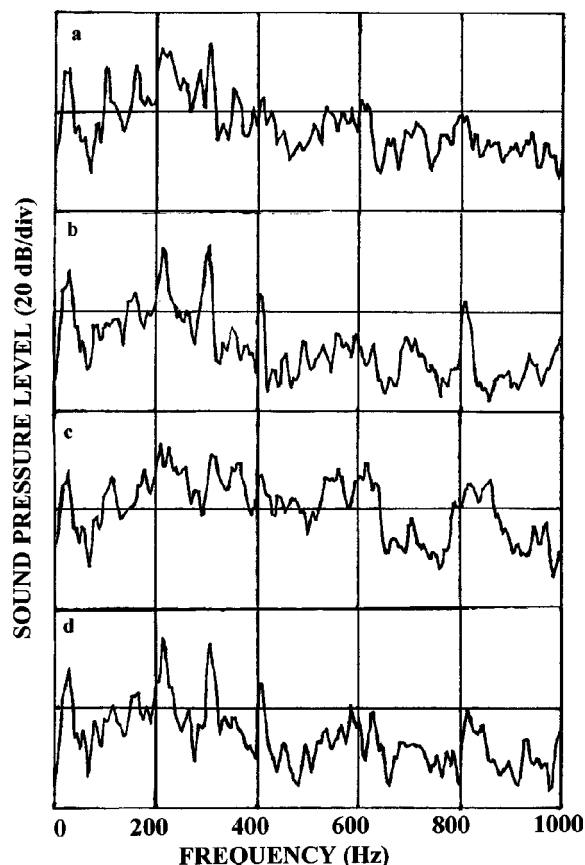

FIG. 8. Room-averaged sound levels recorded at 1 m. (a) Front: driven on the bass side of the bridge; (b) back: driven on the bass side; (c) front: driven on the treble side; and (d) back: driven on the treble side. A linear frequency scale is used.

1998). Substituting an undivided bridge made such a mode observable.

Other luthiers have experimented with bracing techniques that result in a top plate with low effective mass. Australian luthier Greg Smallman has pioneered the use of thin top plates with a lattice of light-weight braces of synthetic material such as carbon fiber and epoxy. Combining the low-mass top with a strong bridge, heavy ribs, and back has led to approval of his guitars by performers such as John Williams (Caldersmith and Williams, 1986). Frequencies of the (1,0), (0,1), and (2,0) modes in Smallman's guitars tend to be lower than in most classical guitars, however (Caldersmith, 1989).

Holographic interferometry provides the best spatial resolution of any method used to observe operating deflection shapes of vibrating structures from which the normal modes can be deduced. Recording the interferograms on photographic film is a time-consuming process, however. Electronic TV holography, in which the interferograms are displayed on a TV monitor each $\frac{1}{30}$ of a second, offers one the opportunity to view the patterns of vibration nearly in real time. Phase modulation allows one to determine the deflection phase in order to determine how well the normal modes are approximated by the operating deflection shapes observed (Engström and Rossing, 1998), although that feature was not employed in the studies reported here.

Although this investigation focused mainly on determining the normal modes of a guitar with radially braced top and back plates, it also revealed some interesting features of the radiated sound field which deserve further investigation. One is the rather large difference in the front and back sound levels at 101 Hz, especially when the guitar is excited on the bass side of the bridge, as compared with the small difference in the front and back sound levels at 210 Hz. Since the front and back plates show comparable amplitudes at both frequencies, the difference is apparently due to greater soundhole radiation at 101 Hz.

V. CONCLUSION

Electronic TV holography is an accurate and convenient way to study the normal modes of vibration of musical instruments, such as a classical guitar. Understanding the normal modes of vibration allows the luthier to adjust their frequencies and thus sculpt the tonal design of the guitar. The guitar is a comparatively young instrument, and its design is still evolving.

The normal modes of vibration at low frequencies observed in a classical guitar with radially braced top and back plates appear quite similar to those of traditional guitars with fan bracing. In the mid-frequency range, where modal shapes are more dependent on bracing configuration, radial bracing appears to enhance some modes that radiate efficiently. Radial bracing offers the luthier a desirable option for experimentation and possible improvement of sound quality.

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